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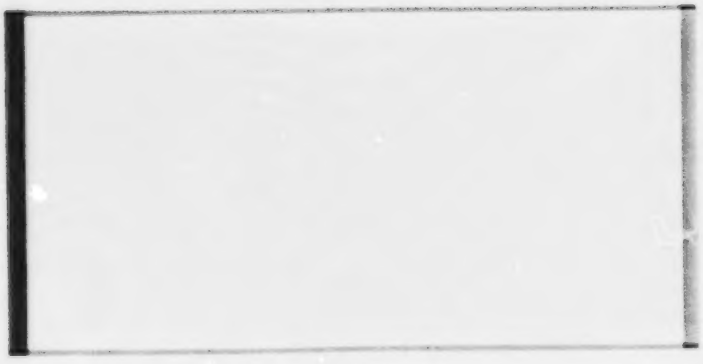

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MICROBIAL EFFECTS - RADIOACTIVE WASTE DISPOSAL SUMMARY REPORT

Report No 85-271-K

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ABSTRACT

The long term safety and integrity of radioactive waste disposal sites proposed for use by Ontario Hydro may be affected by the release of radioactive gases. Microbes mediate the primary pathways of waste degradation and hence an assessment of their potential to produce gaseous end products from the breakdown of low level waste was performed. Due to a number of unknown variables, assumptions were made regarding environmental and waste conditions that controlled microbial activity; however, it was concluded that ^{14}C and ^{3}H would be produced, albeit over a long time scale of about 1500 years for ^{14}C in the worst case situation.

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EXECUTIVE SUMMARY

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V.J. Sharpe
Biologist
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Chemical Research Department

Shallow land burial is being considered by Ontario Hydro for the long term disposal of low level radioactive waste and hence the associated technology is undergoing a comprehensive assessment. The long term safety of disposal sites will be affected by radionuclide migration, where formation and subsequent release of radioactive gases may be an important aspect. Microbes mediate the primary pathways of waste degradation and therefore this report contains an evaluation of their potential to produce gaseous products from waste breakdown.

The approach taken was to select the biochemical pathways of importance based on the composition of the waste and then to determine the level of microbial activity by identifying general- and pathway-specific limiting conditions expected to exist within the disposal trench. To encompass a range of possible outcomes, two scenarios were chosen, with complete maintenance of trench integrity as the best case situation, and rupture of the concrete lining with consequent ingress of groundwater as the worst case scenario.

It was concluded that the mobilization of ^{14}C and ^{3}H can occur through the processes of cellulose decomposition, methanogenesis, bicarbonate utilization, denitrification, sulphate reduction and degradation of aromatics. Of the general conditions within the trench the severest constraints to microbial metabolism are oxygen-free conditions, a highly alkaline pH caused by the concrete backfill, and the availability of moisture and substrate. Due to a lack of defined information on trench conditions, assumptions had to be made. However, it was concluded that for the best case scenario microbial activity would be reduced but not prevented and the volumes of methane and carbon dioxide produced would be considerably less than the maximum theoretical yield. The worst case scenario was similar

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to, but due to the concrete backfill, not as extreme as that experienced in shallow land burial sites in the United States of America. In these instances, after 11 years of operation, 0.05 to 0.075% of the tritium inventory was lost annually and a combination of theoretical calculations and field measurements allowed the prediction that within 1500 years all the ^{14}C would have been converted to CH_4 and CO_2 and released to the atmosphere.

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TO: Mr. H.N. Isaac
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MICROBIAL EFFECTS - RADIOACTIVE WASTE DISPOSAL
SUMMARY REPORT

1.0 INTRODUCTION

This work, requested by the Nuclear Materials Management Department, forms part of a comprehensive assessment of the disposal technology for low level radioactive waste generated by Ontario Hydro's nuclear power stations. The long term safety and integrity of disposal sites will be affected by migration of radionuclides, where formation and subsequent permeation of the surrounding geomedia by radioactive gases may be an important aspect. Micro-organisms and the processes they mediate are being considered because they are primarily responsible for the degradation of both organic and inorganic materials, where the resultant metabolic end products are often gaseous.

Supportive evidence for the role of micro-organisms has been provided by the detection of tritiated and carbon-14 contaminated gases vented from shallow land burial sites located in the USA (Kunz, 1982; Francis et al, 1980a). The extent to which microbes are involved in the generation of gases has not been fully categorized for a number of reasons, but it is generally agreed that they do affect radionuclide mobility under these disposal site conditions (Francis et al, 1980b; Champ and Merritt, 1981). However, extrapolation of such conclusions to Ontario Hydro's situation is partially limited by some basic differences in disposal trench design.

The objective of this assessment is to determine the potential for gas production by microbial processes from low level radioactive waste disposal sites to be used by Ontario Hydro. The approach taken was to ascertain the likelihood of microbes being present in the disposal trench and then, based on the composition of the waste, identify the biochemical pathways and end products of probable importance. The type and extent of microbial activity, and hence the relative volumes and rate of gases produced, are discussed in relation to the environmental conditions thought to exist within the disposal trench. To encompass a range of outcomes, two scenarios were considered; one

in which total containment was assumed, and a second, worst case scenario, where rupture of the concrete lining and backfill with consequent ingress of groundwater was assumed. Throughout the report, areas where information was deficient were identified so that recommendations for improving predictions could be made. A glossary of terms used in this report is given in the Appendix.

2.0 MICRO-ORGANISMS INVOLVED

Micro-organisms could be transported to a disposal trench from one of three major sources. They exist naturally within geological formations and will therefore surround the trench and may be introduced during the construction and trench backfilling phases. The waste itself may contain contaminant organisms from its point of origin. During temporary storage of the compacted cardboard bales damaged plastic casing may allow entry of aerobic microbes attached to particles suspended in air.

3.0 GENERAL LIMITATIONS OF MICROBIAL ACTIVITY

For an active microbial population to develop and maintain growth, certain nutrient and energy requirements must be met. Cellular reproduction needs carbon, nitrogen, phosphorus and sulphur sources plus minerals and an energy source. Biochemical liberation of energy in the absence of light must have: (i) an electron donor, which can be an oxidizable organic compound in the case of chemoheterotrophic organisms or oxidizable inorganics such as molecular hydrogen, ammonia, sulphide and ferrous irons for chemoautotrophic organisms, (ii) an electron acceptor such as molecular oxygen, sulphate, nitrate, carbon dioxide, ferric compounds and simple organics. The carbon source can be supplied by dissolved organic matter, carbonates and dissolved CO_2. Microbes possess broad metabolic capabilities with diverse nutritional requirements and therefore it is probable that the nutrient status of the waste and repository will be suitable for growth of at least some species (West *et al*, 1985; Mayfield and Barker, 1982; Colombo *et al*, 1982).

The other major constraints on microbial activity are environmental conditions within the trench. It has been demonstrated that microbes can tolerate and even thrive under a remarkable range of habitats such as: temperatures ranging from $-7^{\circ}C$ (Inniss, 1975) to $100^{\circ}C$ at atmospheric pressure (Heinen and Lauwers, 1981), pH values from 1.0 to 13.0 (Vallentyne, 1963), high pressure of 180 MPa (West *et al*, 1985), high radiation levels up to 5×10^2 krad (Nassim and James, 1978), a wide range of Eh values +850 to -450 mV (Vallentyne, 1963) and low available moisture levels as indicated in this case by a high salinity

value of 50% salt by weight (West et al, 1982b). In general terms, it is expected that certain groups of microbes will be capable of existing within Ontario Hydro's disposal trenches.

The biochemical pathways which will function and the level of activity are defined by two dominant factors, oxygen tension and pH. Once the trenches have been sealed a combination of remaining aerobic microbial growth and possible corrosion of iron canisters will render the atmosphere anoxic (oxygen free). Within the compacted cellulosic waste this will be the primary consideration. External to the waste packages, and maybe within them at a much later stage should moisture migrate from the backfill, the highly alkaline pH due to the surrounding concrete will severely limit microbial growth.

The other environmental conditions are expected to exert less of a selective pressure but affect the level of microbial activity. These are discussed in relation to specific biochemical pathways in the following sections.

4.0 MICROBIAL PATHWAYS FOR GAS PRODUCTION

The type and concentration of nutrients in the trench, ie the waste composition, will dictate the biochemical pathways that are feasible. Analysis of the plastic-wrapped cardboard bales has indicated a 60% content of cellulosic waste (cardboard boxes, paper, clothing), 20% plastic, plus proteinaceous, aromatic, lipoidal and polysaccharide components of food, some animal carcasses, scintillation fluid and hydraulic oils.

4.1 Cellulose Decomposition

As a major carbonaceous component the degradation of cellulose is a key step in the breakdown of the waste, particularly as radionuclide mobilizing processes such as methanogenensis are dependent upon the liberation of CO_2 or H_2 and fatty acids from prior metabolic pathways. There is a wide range of fungi and bacteria which can degrade cellulose under aerobic conditions, but the organisms capable of anaerobic breakdown are far fewer in number. Although commonly found in soils, the limited number of anaerobic bacterial genera of interest, Actinomyces and Clostridium, will decrease the potential for rapid degradation. Additionally, because organic carbon sources are required as carbon sources and electron acceptors in fermentation pathways, the process is less energetically favourable than aerobic growth. This means that for the same size of population anaerobic bacteria require more substrate than aerobic bacteria and so the efficiency of cellulose breakdown will be reduced. Available surface area of

the substrate also limits degradation and so the cardboard boxes in particular provide an unfavourable surface for attack, unless the constituent fibres swell due to moisture.

Another crucial factor controlling microbial metabolism is the energy:nutrient ratio, which for convenience sake can be expressed as carbon:nutrient ratio. For biosynthetic processes to occur, the uptake of nutrients can only occur through expenditure of energy derived from degradative pathways. Decomposer organisms possess relatively narrower carbon:nutrient ratios than the substrate they wish to utilize and hence nutrients in general, and nitrogen in particular, frequently limit growth yields. To define one upper limiting ratio is open to criticism for a group of organisms as diverse as microbes, but as a guide, wood, which is only very slowly degraded has a C:N ratio of 157 (Swift et al, 1979). As mineralization progresses, releasing CO_2 to the atmosphere, and nutrients such as nitrogen are immobilized, the ratio will improve to a point (C:N<25) where nitrogen is no longer limiting. In the case of cellulosic waste the implication is that once degradation has been initiated the process will continue, albeit slowly.

All of these parameters can increase the lag time before initiation of degradation and decrease the rate of breakdown. However, as there is no definitive information on nutrient and environmental factors it is not possible to provide a quantitative assessment of gas production.

In terms of radionuclide mobility, cellulose degradation will not have a direct effect, but as a result of this activity more accessible intermediate substrates and CO_2 will be produced which will provide energy and nutrient sources for other microbial groups, specifically the methanogenic bacteria.

4.2 Methanogenesis

Methane formation will only occur if organic breakdown produces suitable nutrients and energy sources (fatty acids, CO_2, H_2) (Ontario Hydro Research Division Report No 81-385-K) and the oxidation-reduction potential (Eh) is sufficiently reducing (-200 to -1000 mV) (Colombo et al, 1982). Production of methane and carbon dioxide, the end product of methanogenesis, increases with moisture content, with an optimum around 60-80 per cent (Van Engers, 1982). Higher temperatures also enhance activity with methanogenesis occurring between 4-45°C with an optimum of 35-42° (Weiss et al, 1982). Should highly alkaline waters reach the degraded carbonaceous waste then inhibition of methane formation could occur as activity has only been measured over a pH range of

5.4-8.4 (Rees, 1980), with the exception of Methanococcus vanniellii which possesses an optimum between pH 7.4-9.2 (Stafford et al, 1980). It would seem that the environmental conditions probably present within the disposal trench would severely reduce the amount and rate of methane generated but not its existence, assuming that prior degradative processes have occurred.

The potential for incorporation of radionuclides into methane and carbon dioxide is high because the fatty acid precursors may originate from contaminated organic wastes and the CO_2 and H_2 are likely to contain ^{14}C and ^{3}H isotopes. There is a great deal of evidence that, as a result of microbial activity, radioactive methane and carbon dioxide are vented from shallow land burial sites in the United States (Kunz, 1982; Lu and Matuszek, 1978). However, a lack of precise information on original trench inventory has precluded quantitative assessments of the extent of radionuclide 'carryover.'

Quantitative evaluation of the degree and rate of conversion of waste to gaseous end products is hampered by similar limitations. Theoretically the yield of methane (CH_4) and carbon dioxide (CO_2) from glucose, which is the basic unit from which cellulose is constructed, is given by:

1 kg $C_6H_{12}O_6$ --> 0.25 kg CH_4 + 0.69 kg CO_2 + 0.056 kg dry biomass + 632 kJ heat

(after Pirt, 1978). The CH_4 and CO_2 component is equivalent to 0.7 m^3 gas at standard temperature and pressure. Comparison between theoretical yields (0.7 m^3 for CH_4 and CO_2 kg^{-1} glucose), optimized anaerobic digesters (0.23-0.32 m^3 gas kg^{-1} wet refuse) and experimental soil columns more closely simulating landfill conditions (0.0005-0.039 m^3 kg^{-1} refuse [Rees, 1980]), illustrates the decrease in conversion efficiency under 'real life' situations. It should also be noted that the ratio of CH_4:CO_2 produced varies greatly depending upon the nature of the original carbon source and temperature (Ontario Hydro Research Division Report No 81-385-K).

The design of the shallow land burial sites in the USA has resulted in ready ingress of water, so that despite a lack of readily degradable waste, the conditions supported a relatively high level of degradative/gas forming capacity. Trench gas samples have been found to contain primarily CH_3T and HTO, but also HT, other tritiated hydrocarbons, $^{14}CO_2$, $^{14}CH_4$ and other ^{14}C-hydrocarbons (Lu and Matuszek, 1978).

The various methods used to calculate and present data help to confound attempts at predicting radioactive gas releases by comparing theoretical and field-derived data. In the case of disposal trenches in the USA (West Valley, New York), measurements of concentrations of CH_3T (29.6 Bq cm^{-3}) and trench gas pressure were developed into a model to produce estimates of the extent of release of tritiated methane annually (148 GBq) (Lu and Matuszek, 1979). For the same trench (5), another estimate using an incidental gas production rate combined with the assumption that the effluent gas consisted predominantly of methane, which is unlikely as the ratio of methane to CO_2 decreases as the organic carbon content of the waste drops, gave an annual total release of 222 GBq CH_3T (Lu and Matuszek, 1979). Values for the original inventory are required to ascertain the fraction of trench tritium inventory released as gas. These researchers produced a figure of 296 TBq for trench 5 based on burial and pumping records and an assumption that miscellaneous waste contained no tritium. The latter assumption may result in an underestimate of tritium inventory up to 50%. However, using the values given it can be calculated that 0.05-0.075% of the tritium inventory is released annually from a trench approximately 11 years after disposal of the waste. If one assumes a consistent rate of loss then the entire tritium inventory will be transmitted to the atmosphere within 1300-2000 years. The implication for tritium is not so critical with a half life of about 12 years, but is more serious for ^{14}C (half life of 5568 years). In another assessment of the same disposal site it was estimated that it would take 1500 years for all the carbon to be converted to CH_4 and CO_2 (Kunz, 1982).

For low level waste sites in the USA, it can be seen that irrespective of the accuracy of assumptions and models used to calculate the rate and extent of radioactive gas releases, loss of radioactive gases has been recorded. The proposed design of the Ontario Hydro disposal trenches, in particular the use of concrete backfill, should increase the time before initiation of microbial degradation and hence methanogenesis and retard the rate of gas production. However, in the light of the level of gas lost from trenches in the USA it is concluded that radioactive methane and carbon dioxide will be released from Ontario Hydro sites in the worst case scenario. This scenario presumes the ingress of groundwater, which would carry nutrients, and is similar to conditions experienced in the USA. The limiting factor in this case would be the severe alkalinity of the water, although the impact can only be estimated. If the entire waste was at pH 12 then methanogenesis would not occur as bacteria do not maintain a large difference between internal cytoplasmic pH and external pH (Swift et al, 1979). However, it is well known

that micro-organisms are often active within microsites where the pH is considerably different to the bulk phase pH (Swift et al, 1979).

In fact this situation is indicated by pH data recorded for water samples collected from shallow land burial sites in the USA, where general values for all the sites ranged from pH 2.2-12.4 (Weiss and Colombo, 1978) and more specifically for trenches at Maxey Flats, Kentucky, pH 5.5-12.8 (Clinton et al, 1981) and pH 2.2-12.2 (Cleveland and Rees, 1981). Despite pH extremes recorded for bulk water samples it was apparent that microbial activity and radioactive gas releases existed. The variability in pH conditions for essentially similar trenches at the same burial site is also of note.

4.3 Bicarbonate Utilization

As bicarbonate accounts for a large proportion of the inorganic carbon and ^{14}C inventory, the processes associated with its mobilization are important. This form of carbon is unusable by heterotrophic organisms and can only be metabolized by autotrophs, which obtain their structural carbon from inorganic sources (CO_2, HCO_3^-, CO_3^{2-}) and the necessary energy by oxidizing reduced inorganic compounds (H_2, H_2S, NH_4^+, NO_2^-, Fe^{2+}, Mn^{2+}) (Alexander, 1971). The source of oxidizing power for autotrophs is usually oxygen and so under anoxic trench conditions the number of microbes capable of utilizing an oxidizing agent other than O_2, termed anaerobic respiration, is small.

One pathway is the reduction of CO_2 using H_2 to produce CH_4, both precursors potentially providing for conversion of radioactive species to gaseous forms. This pathway is combined with assimilation of inorganic carbon into the cell that may temporarily immobilize ^{14}C, but has converted it to an organic form, which when the cell dies will be released and then available for utilization by a greater range of microbes. A methanogenic bacterium, Methanobacterium thermoautotrophicum, is capable of this type of metabolism, although it will not initiate degradation as the bacterium requires highly reduced conditions. Another organism capable of mobilizing radioactive bicarbonate is an autotroph, Thiobacillus denitrificans, which uses nitrate as an oxidant instead of oxygen. At NO_3^- concentrations found in groundwaters in the Canadian Shield (approximately 0.4 mg NO_3^- L^{-1}) it was thought that the activity of this bacterium would be restricted (Loewen and Flett, 1984). This would not be the case for some of the USA trenches, our worst case scenario, where nitrate values ranged from <0.05-21 mg NO_3^- L^{-1} (Clinton et al, 1981). These organisms will also increase the pool of organic

carbon, thereby enriching the nutrient environment which will in turn encourage growth of a broader spectrum of organisms. Similarly, other organisms capable of using inorganic carbon under anaerobic conditions, such as the nitrogen fixing Xanthobacter autotrophicus, and nitrate-reducing Paracoccus denitrificans (Ontario Hydro Research Division Report No C85-38-K) will initiate the bicarbonate mobilization process.

4.4 Degradation of Organic Compounds

A major source of nutrients for microbial growth in disposal trenches is organic compounds, which are generally the most amenable to breakdown by the largest group of micro-organisms using fermentation and anaerobic respiration processes. Cellulose degradation and methane generation, which fall into this category, have been dealt with elsewhere. There are multiple pathways by which organics can be degraded anaerobically; they include denitrification, followed by sulphate reduction and then methane generation. A primary indicator of the potential for microbial activity is the concentration of dissolved organic carbon (DOC) available for conversion. Analysis of trench waters retrieved from the Maxey Flats facility in the USA showed values for DOC ranging from 5.1-1,900 mg L^{-1} (about 0.005-2.0 w/v) (Clinton et al, 1981). General heterotrophic activity is thought to decline at DOC concentrations between 50-500 mg carbon L^{-1} (Loewen and Flett, 1984), although for some marine organisms growth has been demonstrated at 0.1 mg carbon L^{-1} (Zobell and Grant, 1942). A comparison of DOC values seems to indicate that, in general, microbial activity would not be limited under conditions equated with the worst case scenario. In an assessment of the capacity of backfill material (clays and shales) to support microbial growth which contained 0.5-5 per cent organic carbon w/w (assuming that organic matter is 50% carbon - Kuznetsov et al, 1963), a similar conclusion was reached (Mayfield and Barker, 1982). To determine whether microbial growth would be restricted under conditions expected for the best case scenario, more specific information is needed.

Denitrification, an anaerobic process whereby nitrate acts as an oxidizing agent in the breakdown of organics, is obviously limited by the availability of nitrate. It is common that nitrogen will restrict microbial activity as many environmental systems are nitrogen limited, and in one study it was felt that denitrification would not be an important process in many disposal trenches at the Maxey Flats site (Dayal et al, 1984).

Of more importance is sulphate dissimilation where sulphate is reduced to sulphide and organic compounds are oxidized, often only partially to produce a pool of fatty acids and CO_2. The accumulation of these products is significant as they may serve as substrates for methane formation. Additionally, these organisms may temporarily reduce tritiated gas levels because they can incorporate hydrogen while using it as an energy source. Sulphate-reducing bacteria are ubiquitous within terrestrial and aqueous environments and so it is difficult to pinpoint a sulphate concentration that would limit their growth. However, even in an enriched culture medium designed to grow these bacteria the sulphate concentration used ranges from 50-250 mg L^{-1} (Postgate, 1979). Measurement of sulphate levels in trench leachates at Maxey Flats, USA, may be somewhat misleading as low values could indicate that sulphate reduction had already occurred leaving minimal sulphate behind. However, sulphate concentrations in the trenches ranged from <1.0-1,700 mg L^{-1} indicating that some sites would support extensive sulphate reducer populations as long as Eh is poised at -100 mV or less (Postgate, 1979). Data for this critical parameter show that chemically-reducing conditions are present in all monitored trenches at Maxey Flats (0 to -100 mV) but that only one trench was below -100 mV (Dayal et al, 1984). Therefore, parallels between these trenches and the worst case scenario indicate that at least some sulphate-reducing activity, and hence a major degradative pathway which also acts as a precursor for methane generation, would occur. A similar conclusion was reached in a microbiological study of trench leachates where it was demonstrated that sulphate-reducing, denitrifying and methanogenic bacteria were not only present but all capable of growth on the leachates (Dayal et al, 1984). Further supportive evidence is supplied by a laboratory study of microbial activity within trench leachates where anaerobic degradation of organic compounds occurred, albeit slowly (Francis, 1981).

The remaining pathway of interest is the potential for breakdown of aromatic compounds, which are normally degraded under aerobic conditions. It is well recognized, and has been demonstrated, that aromatics become more resistant to microbial attack upon creation of anaerobic conditions (Tate, 1979). It has been frequently cited that anaerobic micro-organisms are capable of aromatic ring decomposition (Guyer and Hegeman, 1969; Dutton and Evans, 1969), although it is not mentioned that the organisms studied require light and therefore could not function under trench conditions. More importantly, there is evidence that a wide range of organisms, many not fully characterized, will degrade aromatics anaerobically during nitrate respiration (Williams and Evans, 1975) and methane formation (Healey and Young, 1979; Balba and Evans, 1977; Mah et al, 1977). It would

appear that in these cases consortia of microbes are necessary for complete degradation of aromatic nuclei, making it even harder to pinpoint limiting conditions. It has been concluded by others (Colombo et al, 1982) that under trench conditions anaerobic breakdown of aromatic polymers would be minimal.

4.5 Breakdown of Plastics

Plastics are highly recalcitrant materials and there is little information on their breakdown, particularly under anaerobic conditions. Leaching, which presumes high moisture levels in the disposal trenches, weakens plastics by removing plasticisers thereby increasing exposure of the polymer backbone to enzymatic and chemical action (Rees, 1980). It is to be expected then, that there will be little microbial decompositon of plastic. One important observation in sanitary landfill sites was that plastics remained impermeable to water after a year's exposure to landfill leachate (Rees, 1980). In terms of low level radioactive waste disposal, it seems possible that, within plastic casing, microbial activity would be unhindered by the highly alkaline pH environment of the concrete backfill for some time after trench closing.

5.0 ACID PRODUCTION

Assuming that there will be sufficient moisture for migration of water from the concrete backfill to the buried waste, the highly alkaline pH would likely inhibit much of the potential microbial activity. A second assumption is that the organisms would actually come into contact with this water, which would probably only occur under the worst case scenario, in which case this may be the major limiting factor for this scenario. Under the best case situation excess water is not anticipated, which may actually be detrimental from a safety standpoint as large volumes of alkaline water may not reach the microbes. The basis for this conclusion is that microbes can produce acid on a local basis so that within microsites there is potential for neutralization of alkalinity. Partially degraded carbonaceous compounds include acids and alcohols (Colombo et al, 1982) and acids are derived from protein metabolism (Rees, 1980). More specifically, the Thiobacillus species associated with nitrate reduction will increase acidity (Loewen and Flett, 1984; West et al, 1985) and acetogenic bacteria produce acetic acid from carbon dioxide and hydrogen under strictly anaerobic conditions (Ontario Hydro Research Division Report No C85-38-K). However, there are microbial processes that produce alkalinity, such as sulphate reduction, de-amination of amino acids and denitrification, to counteract the acidity. Overall, microbial acid production cannot neutralize all the backfill alkalinity, but this would not

be necessary to allow some organisms to be metabolically active within microsites.

6.0 CONCLUSIONS

The ability to derive conclusions from the available information is limited by two main factors, a lack of specific data on environmental conditions and the existence of too many undefined variables. The environmental conditions within Ontario Hydro's disposal trenches are not defined, neither are the fluctuations in biological and chemical parameters likely to occur during trench operation. Even improved description of such conditions will not allow determination of the accessibility of the wastes to microbes, a critical factor (West et al, 1985) which will likely vary considerably within individual waste packages. There is very little information on non-optimized growth rates of micro-organisms within any environment (Mayfield and Barker, 1982), let alone on the activity of microbial consortia performing complex interacting degradative pathways within disposal trenches. Therefore, estimation of the extent and rate of release of radioactive gases to the environment from an undisturbed Ontario Hydro low-level waste site, the best case scenario, is highly speculative at best. However, it could be said that:

i) initially viable micro-organisms will be present in some of the waste packages, and that some of these organisms can function under oxygen free conditions;

ii) judging from the visual observation of moisture in about 9 per cent of the waste bales, that complete exclusion of water, and hence of microbial growth, is not likely;

iii) that mobilization of ^{14}C and ^{3}H can potentially occur via the processes of cellulose decomposition, methanogenesis, bicarbonate utilization, denitrification, sulphate reduction and degradation of aromatics;

iv) that the extent of microbial activity cannot be determined from the currently available literature;

v) that theoretical yields of methane and carbon dioxide from glucose, ie from cardboard which represents the bulk of the waste, is 0.7 m^3 gas per kg glucose, but that this value is greatly reduced under sanitary landfill conditions, which are considerably more conducive to microbial activity than radioactive waste disposal sites.

In contrast, the worst case scenario, as represented by the shallow land burial sites in the USA, allows for more certain predictions. In assessments of microbial activity, both controlled experiments using leachate removed from these trenches (Francis, 1981) and field-derived data from analysis of leachate components (Dayal et al, 1984) produced the conclusion that microbes were both present and active within the disposal sites. As a result of their metabolism radioactive gases were being released to the atmosphere. For shallow land burial sites in use within the USA, a combination of theoretical assessments and field measurements revealed that:

i) trench gas samples were found to contain mainly CH_3T and HTO, but that other tritiated forms plus $^{14}CO_2$, $^{14}CH_4$ and ^{14}C-hydrocarbons were present;

ii) estimates for release of CH_3T ranged from 148-222 GBq CH_3T from a single trench per annum;

iii) 0.05-0.075% of the tritium inventory is released annually from an 11 year old trench;

iv) it was thought that within 1500 years all the carbon would have been converted to methane and carbon dioxide with the consequent release of ^{14}C.

However, it should be remembered that one of the major differences between the design of these trenches and those to be used by Ontario Hydro is the presence of concrete backfill in the latter. The only likely sources of information on the effect of concrete backfill are the Swedish and French situations and as yet data from the Swedes have not been forthcoming and the values for releases of radioactive gases from the French sites are classified information.

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APPENDIX 1

GLOSSARY

Aerobic	(of an environment) where there is free oxygen at partial pressures similar to those found under normal atmospheric conditions
Anaerobic/Anoxic	(of an environment) where there is an absence of free oxygen
Autotroph	An organism that uses carbon dioxide as the sole source of carbon (for growth), while energy for growth may be supplied by light (photoautotroph) or derived for inorganic substances (chemoautotroph)
Chemoautotroph	An organism that obtains its energy and carbon from chemical reactions involving strictly inorganic sources, excluding light
Chemoheterotroph	An organism that obtains its carbon from an organic carbon source while its energy may be derived from chemical reactions involving either inorganic or organic sources, excluding light
Cultures	A growth of a particular type of micro-organism on or within a solid or liquid nutrient medium
Cytoplasmic	Essential living matter of any cell inside a cell wall but outside the nucleus
Electron Acceptor	Oxidizing reagent - a compound or element which gains an electron and/or hydrogen atom
Electron Donor	Reducing agent - a compound or element which loses an electron and/or hydrogen atom
Facultative	(adj-optional) Refers to the ability of an organism to adapt to an alternative life style or mode of nutrition
Heterotroph	Organism which requires a source of exogenous organic compounds for growth and reproduction
Methanogenic	(adj of bacteria) which are capable of energy production through the process of anaerobic oxidation of hydrogen gas, using CO_2 as the

	electron acceptor, the metabolic products of which are methane (CH_4) and water
Methylotroph	(adj of bacteria) which use methane as the sole source of carbon through a strictly aerobic pathway which has not been fully elucidated
Micro-Aerophilic	Refers to oxygen concentrations which are much less than normal atmospheric levels but are not anaerobic
Obligate	Refers to any state or condition which is an essential attribute of a given organism
Thermophilic	Pertaining to optimum temperatures for growth of micro-organisms which exceed 45°C
Vegetative	Of cells - which are involved in nutrition and growth, ie not reproductive or dormant forms